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by

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ABSTRACT This article systematically summarizes the newest progress in spacecraft reentry orbits and control. Analyses are made of research results obtained from 9 specialized topics as well as of problems which exist and trends in development. These specialized topics are such ones as the presentation and significance of optimized reentry orbit calculations and control problems, characteristic indicators associated with reentry flight orbits, optimized reentry orbit approximation calculations and precision numerical value solutions, reentry guidance and control systems, various types of optimized aeroassisted orbital transfer problems, composite spacecraft navigation systems, small model reentry body aerodynamic characteristics and control problems, defense penetration and interception problems during reentry flights, a number of mutual relationships between reentry problems, and so on.

KEY TERMS Reentry spacecraft Reentry orbit Flight control

1 PRESENTATION AND SIGNIFICANCE OF REENTRY ORBIT CALCULATION AND CONTROL PROBLEMS

Reentry refers to spacecraft flying from outside the atmosphere back into the atmosphere. From considerations of flight orbit terminal constraints, reentry includes content from two areas. One type refers to spacecraft returning to the ground from the upper edges of the atmosphere (approximately 120km off the ground) (called return type reentry flight). It can also be divided into glide type reentries associated with large lift to drag ratios as well as ballistic type reentries associated with small lift to drag ratios, and so on. The other type refers to spacecraft flying out of the atmosphere again after flying into the atmosphere. The purpose is to realize space orbit maneuvers. These are designated as aeroassisted orbital transfers. They can be divided into orbital transfers within the same plane as well as within different planes, and so on.

Reentry spacecraft can be divided into space shuttles (space planes), (manned) spaceships, satellites, warheads, and so forth. They can also be divided into manned and unmanned reentry spacecraft and can still be divided again into reusable and nonreusable spacecraft, etc. Even though lift to drag ratios as well as ballistic parameters, and so on, associated with various types of reentry spacecraft are not the same, their reentry orbits and control, however, have a good number of common problems. We will now summarize as follows.

1.1 Reentry Orbit Calculation and Optimization as well as Orbit/Thermal Protection System (TPS) Selection Problems

During orbital flight movements, spacecraft possess huge energies (for example, speeds are around 7.8km/sec). This brings with it three problems associated with optimum selection of reentry orbits.

(1) Severe Aerodynamic Heating Causes TPS Mass to Increase. During reentry flight processes, severe aerodynamic heating will be produced. For example, temperatures associated with space plane nose cone tips can reach 1650°C. Spaceships or warheads with relatively large reentry angles are, by contrast, far higher than this temperature. If one does not have TPS, reentry spacecraft will inevitably burn up. This makes reentry spacecraft TPS masses account for 7%-20% or more of reentry body mass. /2

(2) Dynamics Problems. Due to reentry spacecraft time periods being generally 3000-40s, there is a need to take intial reentry contraints and turn them into terminal constraints. Relatively large normal and axial overloads will then be produced during flight processes. For example, maximum normal overloads during space shuttle reentry processes are capable of reaching 2g (sustained approximately 10min). Spaceship axial overloads are capable of reaching 8g (sustained approximately 30s). Maximum normal overloads associated with small model reentry bodies such as

warheads can, by contrast, reach over 20g. However, loads which people and spacecraft structures are capable of bearing are limited in all cases.

(3) Costs of Minimum Overall Masses in Reentry Flights. The costs of overall masses include TPS mass and engine fuel mass when leaving orbit (and entering orbit). As far as optimum selection of brake pulse speeds when leaving orbit (equivalent to engine fuel mass) is concerned, it is possible to very, very greatly reduce overall mass costs, thereby very, very greatly increasing useful load[1].

Summarizing, it can be seen that, with regard to studying a type of method for orbital calculations with good characteristics and optimization, searching out reentry orbits which possess optimal thermodynamic environments (return orbits and aeroassisted orbital transfers) and--going a step further, increasing useful loads--is a problem with great theoretical and engineering value. This is also precisely one of the hot topics of research for the last over 30 years and, in particular, inside and outside China at the present time[3].

1.2 Navigation Problems During Reentry Flight

Due to reentry flight environments being very bad as well as other special requirements associated with spacecraft design, a good number of demands have been posed for navigation systems. For example:

(1) High Precision, Reliability, and Error Tolerance Requirements. Because reentry flight is often unpowered flight (or very conservative of energy), in conjunction with that, there are requirements to rigorously satisfy terminal constraints. Otherwise, it will lead to the thorough going failure of the flight. Besides that, there exist black barrier zone phenomena during reentry flight processes. For example, at approximately 80km altitude, space shuttles enter black barrier zones. These continue right through until approximately 54.8km altitude (around 20min). In this period, plasma sheaths will cut off GPS navigation, radio navigation, and communications. Furthermore, dynamics environments associated with reentry flight phases (for example, overloads and attitudes) become very violent, bringing with them a definite threat to navigation systems (for example, INS).

(2) Requirements Associated with Light Mass, Small Volume, and Low Price. Lightening of navigation system mass and reduction of their volume is advantageous to increasing useful load. Lowering navigation system manufacturing costs, it is possible to save on funds. In both cases, these are indices which are hoped for during design processes.

As a result, designing composite navigation systems associated with indicators such as high precision, high reliability (malfunction-movement, malfunction-safety), light mass, small volume, low cost, and so on, is an indispensable link in spacecraft design. It has also been a challenging problem for a long time.

1.3 Guidance and Control Problems During Reentry Flight

Various types of random interference sources exist during reentry flight. They are such things as reentry point parameter deviations, atmospheric density deviations, wind, spacecraft lift force and drag force parameter deviations, weight deviations (including mass and gravitational acceleration deviations), guidance navigation and control system model errors, as well as noise, and so on. In this way, spacecraft are made unable to fly in accordance with ideal orbits. In order to eliminate the effects of interference sources, it is necessary to carry out guidance and control with respect to flight orbits, requiring the design of hardware systems with good guidance and control pattern characteristics as well as realizing control rules. Generally, we demand that guidance and control rules as well as their hardware systems possess optimization characteristics, high degrees of reliability (error tolerance characteristics), insensitivity, self-adjustment characteristics, and so on.

1.4 Other Dymanics and Control Problems During Reentry Flights

There also exist during reentry flight processes a good number of flight dynamics and control problems. For example,

a. Roll Abnormality and Control Problems Associated with Spinning Small Model Reentry Bodies. During reentry flight, as far as small model spacecraft with very large ballistic parameters (β=m/CDS) are concerned, due to the existence of the coupled effects of center of mass shifts, small inertia asymmetries, and small aerodynamic asymmetries, it is made so that their spinning speeds have the possibility of being equal to natural pitch angle frequencies, /3

creating roll resonance, or the spinning speeds approach or pass zero. These roll abnormality phenomena (resonance and passing zero) make it so that angles of attack increase in size. Target misses get bigger--even to the point of creating the consequences of catastrophic spacecraft structure destruction. As a result, there is a need to carry out analysis with regard to mechanisms generating roll abnormalities, and, in conjunction with this, effectively going through controls (active or passive) in order to suppress the generation of roll abnormalities.

b. Defense Penertration and Interception Problems During Reentry Flight. In the realm of research on reentry orbits and control, there exist problems associated with precision guidance and maneuver defense penetration of reentering warheads. This is because reentry warheads which do not possess defense penetration capabilities have difficulty hitting targets. In another area, in order to intercept and destroy reentering warheads in a timely manner, it is necessary to set up high, medium, and low altitude interception systems inside and outside the atmosphere. As a result, it is then necessary to resolve problems associated with corresponding optimized interception guidance rules (program

guidance, medium guidance, as well as terminal guidance, and so on).

2 RESEARCH PROGRESS ASSOCIATED WITH REENTRY ORBIT AND CONTROL PROBLEMS

Below, we divide up special topics with respect to the history of reentry orbits and control problems and carry out a brief summary of the current situation. In conjunction with this, the main problems which exist in this are pointed out.

2.1 Reentry Orbit Characteristic Indicators

On the basis of spacecraft types as well as differences in the purposes of reentry orbits, it is possible to take characteristic indicators and divide them into the several types below.

(1) Useful Loads Maximum. A characteristic indicator which possesses clear significance is spacecraft useful load. Spacecraft total mass is

mspacecraft = mpropellant + museful load + mspacecraft structure, thermal protection system, and so on

$$m_{飞行器} = m_{推进剂} + m_{有效载荷} + m_{飞行器结构、热防护系统等} \quad (1)$$

A relatively good measure of the characteristic indicator can be selected as museful load/mspacecraft .

During research processes associated with the optimization of this characteristic indicator, a good deal of research work lies in considerations of TPS mass and orbital designs. Directly optimizing the mass characteristic indicators in question will be accompanied with large amounts of calculations. This is very difficult. In the majority of cases, optimization of these indicators is not direct. Rather, it is optimization of aerodynamic peak values $\dot{q}_{max}$ and total thermal loads Q. Garcia and Fowler directly minimized TPS mass, taking space shuttle TPS surfaces and dividing them into 22 pieces, giving relationship forms between reusable TPS and Q as well as metal TPS pieces and surface temperatures TW and making performance indicator

$$J_1 = m_{TPS} = \sum_{i=1}^{22} m_i[(\dot{q}_{max})_i, \ Q_i] \quad (2)$$

reach a minimum. Eldred and Wurster also did similar work[3].

(2) Total Thermal Load Minimum. Total thermal load refers to the integral of aerodynamic heating rates $\dot{q}(t)$ along flight orbits. $\dot{q}(t)$ generally opts for the use of thermal flow

rates associated with areas of most severe thermodynamic heating. Moreover, $\dot{q}_{max}$ (t) during flight processes is subject to limitations.

(3) Total Overload Minimal. Total overload is the integral of normal overloads n(t) along flight orbits.

(4) Aerodynamic heating rate peak values $\dot{q}(t)$ are minimal. Thermal flow peak values reach minimal performance indicators and are capable of being displayed as (This is a Chebyshev problem.)

$$J_4 = \max \dot{q}(t) \tag{3}$$

(5) Energy Loss Minimal and Terminal Velocity Maximum. This type of performance indicator is primarily used in the atmospheric flight phase of aeroassisted orbital transfers. Terminal velocity maximums and energy loss minimums are equivalent.

(6) Gliding Ranges Maximum. The performance indicators in question can be used in the determination of terminal flight orbits during return type reentry flights.

(7) Total Orbital Inclination Angles Minimal. Total orbital inclination angle refers to the sum of the integrals of squares of orbital inclination angles along flight orbits. This type of performance indicator is primarily used during aeroassisted orbital transfers. It is extremely advantageous to indirect optimization of performance indicator (1). /4

(8) Flight Time Periods as Short as Possible.

(9) Performance Indicators Related to Dynamic Pressures. Dynamic pressure performance indicators are capable of being divided into two types. a. In cases where dynamic pressures are subject to limitations, the sum of integrals of dynamic pressures along orbits reach minimums. b. Dynamic pressure peak values reach minimums, that is

$$J_{10} = \max_t q(t) \tag{4}$$

(10) Other Types of Performance Indicators. Orbital plane angels of inclination are made to become large. High drag forces are minimal and so on.

(11) Comprehensive Forms of Performance Indicators. For example, combination a in performance indicators (2) and (9), combination b in performance indicators (4) and (9), and so on.

2.2 Reentry Orbit Calculations and Optimization

Reentry orbit solutions and optimizations can be divided into approximate solution solution methods and precision numerical value solution methods.

(1) Reentry Orbit Approximation Solutions

Return Type Reentry Orbit Approximation Solutions. There are a great many solution methods associated with approximation solutions of reentry maneuver orbits. Due to the fact that the assumed conditions option is made for the use of are not the same, the levels of approximation of solutions obtained are also different. Research in this area has already produced large numbers of articles. In particular, progress was very fast in the late 1950's and early 1960's. From the 1970's to the early 1990's, foreign scholars in this area also did even more in depth work. Seen overall, all scholars were making assumptions about various terms on the right side in motion equations (that is $\dot{V}$ =f1 , $\dot{\gamma}$ =f2) That is, a. Ignore the effects of gravity, centrifugal force, drag forces, and Ge (phonetic) forces. Only consider the effects of aerodynamic forces. b. When only considering the effects of aerodynamic forces, take lift force parameters and drag force parameters to be invariable. c. Take three dimensional orbits and change them into orbits associated with planar surfaces and verticals to this plane. d. Take orbital angles of inclination to be approximately constants. e. Constant acceleration. f. Believe that--approximately--integrals of the term

$$\left[\left(\frac{1}{\beta R_0}\right)\frac{\cos\varphi}{\rho}\left(\frac{gR_0}{V^2}-1\right)\right]$$

are insensitive with respect to ρ (illegible) . It is possible to take them to be constants, that is, Loh assumptions. g. Approximate matching methods associated with gradual expansion (The space part is precise, but the atmospheric part is approximate). h. Equilibrium glide assumptions used in order to solve for reentry orbits associated with large lift to drag ratios. i. Assumption that flight orbits are four flight stages associated with constant value thermal flow rates, equal overloads, equal dynamic pressures, and energy transitions. j. Other assumptions. Among these assumed conditions, some have single uses. Some have two (or more than two) combined uses. Moreover, a, b, d, and e are only used with spacecraft having small lift to drag ratios. h and i are generally used with manned spacecraft having large lift to drag ratios. However, c, f, and g are appropriate for use with all reentry spacecraft.

Approximate Solutions for Aeroassisted Orbital Transfer Type Reentry Orbits. Aeroassisted orbital transfer spacecraft generally possess relatively large lift to drag ratios in order to provide adequate lift forces to realize orbital transfers associated with atmospheric sections, achieving the objectives of space orbital transfer. As a result, the c, f, and g assumptions above are all appropriate for use with this type of reentry orbit. However, the assumptions for which option is made the most are c and f.

The inadequacies of research on reentry orbit approximate solutions lie in the unified forms of approximation solutions and corresponding optimization control associated with reentry orbits for various types of performance indicators when various kinds of constraining conditions are inadequately imposed. This is not

advantageous--in basic terms--to knowing the internal mechanisms associated with optimum reentry processes.

(2) Reentry Orbit Precision Numerical Value Solutions and Optimization

Opting for the use of numerical values (for example, Longge-Kuta (phonetic) methods) to integrate spacecraft reentry differential motion equations, it is then immediately possible to obtain precision numerical value solutions for reentry orbits. However, generally, aviation engineers all require solutions associated with a certain type of performance indicator to be optimum numerical value solutions. At the present time, all solution methods are based on optimum control and maximum value principles. Following along with the speed of computer calculations as well as increases in storage capacity--since the end of the 1970's--work associated with precise solutions for orbital numerical value solutions associated with the several types of performance indicators above achieved breakthrough progress. This type of optimum control numerical value method can be summarized as follows. a. Projection gradient restoration methods are primarily used in order to solve Chebyshev problems. b. Nonlinear recursion methods VF01A. c. Gradient methods, conjugate gradient methods, generalized gradient methods, as well as /5
improved conjugate gradient methods. d. Pure form methods. e. Scale change methods. f. General numerical value integration methods associated with optimum control. g. One type of direct POST (Program to Optimize Simulated Trajectories) method which opts for the use of parameter optimization in order to achieve optimum control. h. Multiple target hit methods. i. Penalty function methods and weighting parameter change methods. j. Other methods.

These numerical value methods are not only appropriate for use with spacecraft associated with large lift to drag ratios. They are also suitable for use with spacecraft having small lift to drag ratios--not only appropriate for use with spacecraft having single control variable (for example, roll angle) control but also suited for use with spacecraft having multiple control variables (for example, angle of attack and roll angle) control. The inadequacy in this field of research lies in a shortage of optimum return orbit numerical value algorithms when mass costs are minimal as well as selection criteria associated with optimum return orbits obtained from these.

2.3 Reentry Guidance and Control Systems

Generally, reentry guidance makes spacecraft fly in good thermodynamic environments. In conjunction with this, it precisely satisfies terminal constraints. Traditionally, reentry guidance is taken and divided into standard orbit methods and predicted point of fall methods. Theoretical research in this realm--at the end of the 1950's and early 1960's--then achieved very great progress. In conjunction with this, it tended toward maturity. From the beginning of the 1960's to the end of the 1980's, reentry guidance

theory achieved successful applications and development[6]--one after the other--in manned spaceships and space shuttles[5].

(1) Reference Orbit Methods.

Reference orbit methods are one type of comparatively simple guidance system. In this method, a set of orbital configuration parameters are calculated beforehand for values along reference orbits. In conjunction with this, they are taken and stored in spacecraft computers. During reentry processes, option is made for the use of navigation systems to acquire differences between flight configuration real time values and previously existing values in order to control roll angles, so as to make spacecraft return to reference orbits (path control devices) or set up new flight orbits--still capable, however, of hitting the point of fall (terminal control devices). a. Longitudinal Guidance Patterns. Spaceship longitudinal guidance rules can be described as

$$(L/D)_C = (L/D)_0 + K_1 \delta V_x + K_2 \delta h + K_3 \delta V_y + K_4 \delta\eta|_t \quad (5)$$

In the equation, (L/D)C is the needed lift to drag ratio instruction. (L/D)O is the reference orbit lift to drag ratio (projection in the orbital plane). Ki(1,2,3,4) are gain constants.

These can be selected as constants. They can also be selected as variables. δ represents configuration variable error. Vx, Vy, h, and η, in turn, stand for vertical components and horizontal components of spaceship velocity, flight altitude, and longitudinal course. b. Lateral Guidance Patterns. Lateral guidance is realized by controling errors within a certain range by going through course deviation angles[5]. It is also possible to control lateral courses in order to realize it.

There are also other methods among those associated with reference orbits--for example, linear quadratic type guidance patterns, and so on.

(2) Predicted Point of Fall Methods.

Predicted point of fall methods are guidance methods with the purpose of eliminating errors between actual predicted point of fall locations for orbits and predetermined point of fall locations, so as to make actual points of fall and preset points of fall coincide with each other. Due to the fact that computation speeds of modern computers are getting greater and greater, the set up of a relatively high precision prediction model in order to improve the accuracy of rapid prediction methods is a task which is very significant and still awaits study.

a. Spaceship Longitudinal Guidance Patterns. Spaceship longitudinal guidance patterns are

$$\sigma_C = \sigma_0 + f(D, V, \delta\eta)\delta\eta(b_1 + b_2|\delta\eta|) \quad (6)$$

In the equation, σO is preselected reference roll angle. f is gain coefficient. b1 and b2 are selected as constants. D and V are, respectively, drag forces and flight velocities.

b. Longitudinal guidance patterns for space shuttles[5] are

$$(L/D)_C = (L/D)_0 + f_1(D - D_0) + f_2(\dot{h} - \dot{h}_0) + f_4\int(D - D_0)\mathrm{d}t \tag{7}$$

In the equation, (L/D)O are lift to drag ratios for preselected reference orbits. f1, f2, f3 are variable gain coefficients determined by reference orbits. /6

c. Spacecraft Reentry Phase Lateral Guidance. Lateral guidance associated with predicted point of fall methods is of the same type as reference orbit methods.

The realm of the study of reentry guidance still needs to resolve the problem of reentry guidance rules, making them not only possess the good thermodynamic environments which guidance rules associated with reference orbit methods are capable of supplying but also having the functions to deal with the large range of errors and strong interference forces which predetermined point of fall method guidance rules are capable of.

(3) Reentry Phase Control Problems.

Realization of Reentry Phase Orbital Control Through Controling Spacecraft Attitudes. Normally, among spacecraft control and stability systems, there are: a. manual-ratio systems b. electrically transmited operation and minimum pulse systems c. speed stability and control systems, and so on, as well as automatic stability control systems, etc. Generally, standards for spacecraft control system design are: a. minumum mass b. minimum power consumption c. minimum propellant consumption d. minimum volume e. a high degree of reliability. From considerations of control effects, control system designs should have the characteristics set out below: a. the ability to realize optimum control in a certain sense (for example, power consumption minimal, time periods minimally short, and so on) b. possess self-adaptation and insensitivity characteristics in order to handle violent changes in such things as atmospheric density, flight velocity, and so on c. be able to continue operations in cases of double malfunctions, that is, possess error tolerance d. possess distributive and integrated control capabilities in order to combine various control subsystems e. appropriately handle nonlinear problems, precision control problems, and so on, and so on, during control system design processes.

2.4 Aeroassisted Orbital Tranfer Problems

In 1962, the pioneer of aeroassisted orbital transfer--London--put forward opting for the use of a combination of aerodynamic forces and thrust in order to realize spacecraft earth orbit transfers. After that--particularly, in the 1980's--aeroassisted orbital transfer theory achieved very great development. Reference [2] quotes 46 references, making a comprehensive summary of work before 1988. Recently, aeroassisted orbital transfers have also made new progress (illegible). Looked at in general, no matter

what type of aeroassisted orbital transfer it is, the purpose of research in all cases lies in reducing the mass costs associated with orbital transfer. Even if the sums of engine fuel mass and TPS mass are extremely small, this is also equivalent to making spacecraft useful loads maximum. Work in this area can be summarized as follows.

(1) Orbital Transfers in the Same Plane

At the present time, the results associated with the majority of orbital transfers in the same plane are concerned with shifting from an initial orbit (a_0, e_0, ω_0) to a designated orbit (af, ef) However, ω_f is not subject to constraints. Here, a is apogee distance. e is eccentricity. e is the angular distance from ascending node to perigee. The simplest case is shifting from a circular orbit to a circular orbit, that is, e0=ef=0. As far as this type of orbital transfer is concerned, option is only made for the use of aerodynamic forces in order to reduce speed. Option is made for the use of aerodynamic drag forces or lift forces to realize control. Moreover, with respect to lift forces, option is made for the use of angles of attack or roll angles in order to accomplish realization.

a. Minimum Fuel Orbital Changes. When studying minimum fuel orbital changes, aerodynamic heating is not taken into consideration. This type of orbital transfer process is flying from high orbit to the edge of the atmosphere through one braking pulse. Application is made of negative lift forces to make spacecraft fly a course section along the edge of the atmosphere. When energy consumption reaches the point where it is just possible to fly to the designated target orbit, option is then made for the use of positive lift to fly away from the atmosphere. When there is flight along an elliptical orbit to apogee, entry is made into the target orbit through one pulse. This type of orbital transfer possesses four types of forms, that is, Hohmann model forms, hyperbolic model forms, aerodynamic ellipse, and aerodynamic parabolic model forms.

b. Minimum Aerodynamic Heating Orbital Transfers. In order to reduce aerodynamic heating, A. Miele and others carried out optimization simulations with regard to performance indicators set out below--consumed energy mass (or characteristic speed); the sum of integrals of aerodynamic heating along orbits (thermal load); the sum of the integrals of squares of orbital angles of inclination (when flying within the atmosphere) along orbits; peak aerodynamic heating rate values. Interesting conclusions were reached. The first performance indicator is equivalent to the latter two. Moreover, when flying in accordance with the three performance indicators, thermal loads which are produced are better than the optimized results when in accordance with the second indicator[2].

c. Discussion of Other Cases. This includes the influences of maximum L/D on aerodynamic heating and energies, transfers between elliptical orbits, and so on. /7

(2) Orbital Transfers in Different Planes.

The purpose of this type of orbital transfer lies in opting for the use of minimum mass costs to realize transfers between different orbital planes. Content in this area is rich. It is possible to summarize it as a. minimum energy transfers. These include three types--aerodynamic parabolic model forms, aerodynamic elliptical model forms associated with single pulses to leave orbit, and aerodynamic elliptical model forms associated with double pulses to leave orbit. b. Performance indicators associated with the reduction of aerodynamic heating. Miele and others made digital simulations with regard to performance indicators set out below--integrals of aerodynamic heating rates along orbits (thermal load), integrals of the squares of orbital angles of inclination along orbits, peak aerodynamic heating rate values. It was believed that the second term was the best. Moreover, the third term is equivalent to minimum energy transfer model types.

(3) Other Progress Associated with Orbital Transfers.

In respect to the realm of aeroassisted orbital transfer research, there exist a good number of hot topics which urgently await solutions. Among these, the most important problems are the urgent need to set up a set of numerical calculation methods which are capable of directly optimizing various types of aeroassisted orbital transfer orbits (mass costs minimal) and, using universally applicable criteria associated with orbit/spacecraft TPS selection, the development of theory and conclusions associated with aeroassisted orbital transfers possessing a general significance[2].

2.5 Spacecraft Navigation Systems

Ideal navigation systems not only require the possessing of high degrees of reliability and error tolerance. They require, moreover, sums of price and mass weightings as well as reliability ratios to reach minima. During the last 20 years--in the area of spacecraft error tolerant navigation systems--a great deal of work has been done--including sensor malfunction detection and indentification, system restructuring, navigation system hardware redundancy optimization, and so on.

(1) Flight Sensor Malfunction Detection and Identification.

Sensor malfunction detection and identification technology can be roughly divided into hardware redundancy, analytical redundancy, and mixed redundancy methods which combine the two.

a. Hardware Redundancy Methods. Hardware redundancy methods opt for the use of two sets or multiple sets of the same type of sensors in order to provide redundant information. Normally, option is made for 3 sensors to send out the same physical quantity. When differences between the physical quantities sent out by one sensor and the other two are comparatively large, it is then believed that the sensor in question has malfunctioned. When it is required to be able to detect and identify two malfunctions which occur at the same time in association with the same type of sensors, option must be made for the use of quadruple redundancy--

even more hardware redundancy analogous to this.

As far as hardware redundancy associated with quick connect inertial components is concerned, option is normally made for the use of oblique placement type structures in order to reduce the number of redundant components. Making use of gyroscopes with 4 single degrees of speed freedom, it is possible to supply redundant information associated with speed measurements in the directions of 3 perpendicular axses.

The advantage of hardware redundancy is that detection principles are simple, detection speeds are fast, and it is reliable. The drawback is that it requires a lot of duplicative equipment. Costs are high.

b. Analytical Redundancy and Mixed Redundancy Methods. Analytical redundancy opts for the use of various types of dynamic and static digital models associated with such things as carrier body motion equations, navigation system observation equations, filter devices, and so on. These numerical models provide analytical relationships between various measured physical quantities. As a result, they provide redundant amounts of outputed information. Due to the composite navigation systems of advanced spacecraft (for example, space shuttles), they are composed of such things as multiple sensors of the same kind and multiple sensors with the same functions but of different types. This is a very complicated system. Therefore, their malfunction detection and identification methods should be many and various--for example, divided level dispersed type wave filtering methods[8], directly making use of analytical realtionships between the same type of measured value associated with different sensor devices, double hardware redundancy and double observation device designs, malfunction detection wave filters, deviation isolation type malfunction estimation devices, and other methods. Analytic relationships are capable of opting for the use of navigation computer software for realization. It is convenient and reliable. Mixed redundancy, which combines together them and hardware redundancy, possesses such advantages as little duplicative equipment, low costs, fast detection speeds, reliability, and so on. It is a very practically useful malfunction detection and indentification method. The drawbacks of this type of method lie in the fact that, because analytical redundancy is based on using system mathematical models, errors in setting up the models will often influence the correctness of malfunction detection and identification. At the present time, a great many methods have already been put forward in order to improve the insensitivity of malfunction detection and indentification with regard to errors in setting up models as well as other unknown inputs. However, optimum methods should estimate these model errors. In /8 conjunction with this, compensation is made with respect to models.

The reason is that, only in this way is it possible to fundamentally improve the accuracy and reliability of analytic redundancy.

As far as statistical decision making during malfunction

detection and identification is concerned, option is generally made for the use of sequence link probability ratio methods, generalized liklihood methods, and so on. In order to increase malfunction detection insensitivity, it is possible to opt for the use of unkown input filter methods, insensitivity odd/even equation methods, and so on.

(2) System Restructuring of Navigation Systems

Navigation system system restructuring strategies are determined on the basis of such factors as the level of malfunction severity, navigation equipment which generates malfunctions, flight environments, and so on. Equipment malfunctions can be divided into two types--hard malfunctions and soft malfunctions. The appearance of hard malfunctions means that the equipment in question cannot be restored--for example, inertial platforms turning over, and so on. At this time, equipment which has produced malfunctions is abandoned. However, taking the rest of the navigational equipment and recombining it together is possible.

Soft malfunctions of equipment refers to some decline in the precision--for example, gyroscope drift, and so on. It is possible, however, to carry out compensatory calibration with regard to malfunctioning equipment. Navigation system measurement values after doing calibrations are completely or approximately restored to precisions originally possessed. This type of malfunctioning equipment can still continue to be used. With a view to soft malfunctions, it is possible to carry out the system restructurings that follow in regard to navigation systems[8]--direct correction of erroneous configuration parameter methods and automatic adjustment error variance correction methods. References related to navigation system restructuring are still very few at the present time.

(3) Combined Methods Associated with Different Navigational Systems

In different flight environments, spacecraft can opt for the use of different equipment combinations in order to provide needed navigational information. On the basis of requirements, it is possible to combine the equipment below--inertial measurement systems (INS or SINS), GPS radionavigation systems, star tracking devices (STAR), optical alignment observation devices, speed gyroscopes, accelerometers, aerodynamic parameter measurement systems, radar altimeters, Doppler navigation systems, direction finding and range finding systems, Omega navigation systems, astronomical navigation systems, tactical aerial navigation systems, microwave scan landing systems, roll speed measurement sytems, and so on. Combined navigation systems commonly used in spacecraft include GPS/INS combined navigation systems, GPS/INS/STAR combined navigation systems, INS/radio combined navigation systems, etc.

2.6 Dynamics s and Control Problems Associated with Small Model Reentry Bodies

Inside and outside China, there are already a good number of scholars who have done research with regard to small model reentry body roll abnormalities and their control. Seen overall, work in this area can be summarized as research on angle of attack divergence mechanisms, research on low altitude roll resonance conditions, research on roll interlock criteria, approximate analytic solutions associated with trimming angles of attack, physical processes produced by small amounts of asymmetry, influences of roll abnormalities on hit error spread. Research methods associated with this work are based on theoretical analyses associated with approximation formulae as well as approximate solutions, based on numerical value solutions for ballistic equations with six degrees of freedom, flight tests as well as wind tunnel tests, and so on.

Problems which exist are--when considering the effects of various types of asymmetry--analytic solutions for boundary conditions producing roll abnormalities, analytic solutions associated with trimming angles of attack, and so on.

There are many measures to control roll abnormalities. It is possible to summarize them as follows a. reduce mass and inertia asymmetries b. enlarge static margins c. select optimal initial roll speeds d. control the size and direction of moments of roll force produced because of ablation from thermal protection system manufacturing techniques on up e. opt for the use of roll control systems in order to control reentry body roll speeds. They also include 5 types of designs--roll speed control systems, roll speed control systems with fluid acting as moving hydrazine, passive type control systems, semipassive type control systems, as well as angle of attack control systems.

Problems which exist in the control of roll abnormalities require designing compensatory control rules when spinning tail surface ablation is appropriate, controling warhead roll abnormalities and, at the same time, increasing warhead hit accuracy, etc.

2.7 Defense Penetration And Interception Problems During Reentry Flight

2.7.1 Defense Penetration Maneuver and Precision Guidance of Reentry Spacecraft

Theoretical and technological development in this field is already comparatively mature. Generally, defense penetration of reentry spacecraft can be divided into program controled maneuver/9

ballistics and intelligent maneuver ballistics (that is, optimized maneuver evasion rules based on differential countermeasures theory). In regard to defense penetration with precision guidance, there is still a need to resolve optimized guidance rules, high precision orbit determination problems (for example, GPS/INS navigation, and so on), guidance system hardware realization (for

example, radar guidance and imagery matching guidance), as well as overall adjustment rules for guidance, navigation, and control circuits, the influence of defense penetration maneuvers on terminal guidance precision, and so on.

2.7.2 Interception Problems with Regard to Reentry Spacecraft

Normally flight tracks of interceptor missiles are divided into program guidance phase, intermediate guidance phase, and terminal guidance phase. Progress associated with the guidance rules for these three flight phases, composite guidance, as well as the corresponding wave filter theory is briefly described below.

(1) Program Guidance Phase. Program guidance phase performance indicators are generally minimum amounts of energy consumed by engines (or terminal velocities maximal) or intercept times as short as possible, and so on. Solution methods associated with this type of problem normally opt for the use of maximum value principles in optimization control theory in order to make solutions. Numerical value methods associated with solving these problems involving two point edge values and methods associated with the precise numerical value solutions of reentry orbits are the same.

(2) Intermediate Guidance Phase. Intermediate guidance phase performance indicators are the same as program guidance phase. Moreover, there is a requirement to comparatively rigorously satisfy terminal constraints. As a result, this area of guidance rules includes the guidance rule associated with minimal energy consumed (or terminal velocity maximal), the guidance rule associated with intercept times being as short as possible, the guidance rule of perdetermined intercept points, and other guidance rules--for example, three point method guidance, ratio guidance, expansion ratio guidance, and so on.

(3) Terminal Guidance Phase. Quite a few problems exist in the terminal guidance phase. As a result, terminal guidance theory is very rich. Generally, it is divided into two catagories--classical terminal guidance rules and terminal guidance rules based on modern control theory. Classical guidance rules can be divided into line of sight guidance, tracking guidance, ratio guidance (offset ratio guidance, extension ratio guidance, and so on), parallel approach method guidance, and so on. Modern guidance rules can also be divided into three types--guidance rules based on optimum control, guidance rules based on differential countermeasures, and other modern guidance rules. In such areas as the handling of maneuver targets, optimum ballistic characteristic counter jamming capabilities, and so on, modern guidance rules have made considerable progress compared to classical guidance rules [9(illegible)]. However, at the present time, there is still a lack of the ability to effectively overcome random guidance patterns associated with problems of precision guidance and wave filter divergence. There is a lack of optimum guidance rules capable of effectively dealing with targets making large maneuvers at high speeds and, in conjunction with that, considering

projectile links of arbitrary order, and so on.

2.8 Mutual Relationships Between a Number of Reentry Problems

Above, an overall summary has been made with respect to dynamics and control during reentry flights and problems related to them. The authors believe that there are mutual relationships between them. These close relationships are as follows.

(1) Relationships Between Orbital Calculations and Guidance Rules. Orbital calculations provide reference orbits for guidance rules. Guidance rules use orbital calculations as their foundation. Reentry orbits possessing optimal thermodynamic environments and obtained through numerical value solutions generally correspond to reference orbit guidance methods. Reentry orbits obtained through approximation solutions also generally correspond to predicted point of fall guidance methods.

(2) Relationships Between Return Type Reentry Flights and Aeroassisted Orbital Transfers. The theory of aeroassisted orbital transfers was developed on the foundation of return type reentry flights. The two both belong to the catagory of reentry flights. The performance indicators associated with the two are interlinked.

The theory of optimization and orbital calculation methods are completely the same. What is even more interesting is that scholars who did research in the realm of return reentry flight in the early 1980's and before all turned to the study of aeroassisted orbital transfers. Moreover, aeroassisted orbital transfer problems are much more complicated than return flight problems.

(3) Relationships Between Spacecraft Reentry Guidance and Tactical Missile Guidance. The differences between the two lie in the fact that missile guidance terminal constraints are generally only that target miss amounts are zero, process constraints are limited to normal overloads, or minimal as functions of orbit integrals. Terminal constraints associated with spacecraft guidance are generally that terminal positions and speeds are limited in all cases, process constraints are limited to thermodynamic environments, or courses are limited.

The places where the two are the same are that, in all cases, option is made for the use of aerodynamic control, and, in all cases, it is desired to hit a certain (terminal) point. Spacecraft predicted point of fall guidance methods and missile predicted intercept point guidance have areas of similarity, that is, there is prediction of whether or not spacecraft will be able to hit targets during flights in accordance with certain guidance rules--if not, corrections are then made to the guidance rules in question. There are areas of similarity between spacecraft reference orbit methods of guidance and missile terminal guidance, that is, spacecraft optimum reentry orbit flights along /10 thermodynamic environments, in conjunction with that, satisfying terminal constraints, and optimum orbital flights of missiles along dynamic environments, in conjunction with that, satisfying terminal constraints.

Seen overall, spacecraft reentry guidance has inherited a number of technologies associated with tactical missile guidance. It also possesses its own special characteristics. As a result, there exists this type of question--whether or not certain of the newest results associated with tactical missile guidance are capable of application in spacecraft reentry guidance.

3 CONCLUDING REMARKS

In summary, the content of research associated with spacecraft reentry orbits and control depends on research requirements for new models of spacecraft, flight task design, specific design requirements, and so on. It also depends on the level of development of a number of disciplines--for example, flight dynamics, aerodynamics, control theory, computer science, materials science, etc. The former put forward new problems for spacecraft reentry orbits and control. Perfect resolution of these problems indicates that the development of this field is already relatively mature. However, the putting forward of new models of spacecraft and flight tasks will ceaselessly present new problems for this field. Progress in the latter has very, very greatly promoted the development of spacecraft reentry orbit and control research, making study in the fields in question continuously satisfy even higher requirements, and, in conjunction with that, tend toward maturity.

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